PUBLICATIONS

OF THE

Astronomical Society of the Pacific.

VOL. VII. SAN FRANCISCO, CALIFORNIA, FEBRUARY 1, 1895. NO. 40.

SPECTROSCOPIC OBSERVATIONS OF NEBULÆ, MADE AT MOUNT HAMILTON, CALIFORNIA, WITH THE 36-INCH REFRACTOR OF THE LICK OBSERVATORY [BY J. E. KEELER].

[From the *Publications of the Lick Observatory*, Vol. III, 1894.]

Reviewed by Professor B. HASSELBERG, Royal Academy of Sciences, Stockholm, Sweden.

In the second volume (1890) of the *Publications* A. S. P., Professor KEELER gave a preliminary account of his spectroscopic determinations of the motions of some planetary nebulæ in the line of sight. The results there laid before the astronomical public are very remarkable indeed, being not only the first successful attempt in this direction, but also and above all distinguished by so great an accuracy, that they stand in every way unequalled by any observations of this class as yet known to science. It is, then, obvious that a detailed account of these researches should be waited for with very great interest, and, in the above-named memoir, Professor KEELER has given such an account, of which a succinct abstract may be acceptable to the readers of the present periodical.

As well known, the gaseous character of the spectra of planetary nebulæ was discovered by HUGGINS as early as the year 1864. Astronomers are also well acquainted with the results of his researches at this time about the chemical origin of the observed nebular lines, and with the doubts which subsequently arose regarding the assumed relation of the chief line to the spectrum of nitrogen, and the reasons upon which these doubts

were founded. Whereas the chemical interpretation of the third line has proved fully exact, it was soon found that the chief line could have no connection with nitrogen, but was of the same enigmatical character as the second line and the lines which are met with in the spectra of several other cosmical phenomenon, such as the aurora, the solar corona and prominences. In this state of the question, LOCKYER, in connection with his theory of the heavenly bodies, expressed the opinion that the chief nebular line belonged to magnesium, and that it was the remnant of the known bright fluting in the green, which is the most prominent feature of the flame spectrum of this metal. It does not seem improbable that this suggestion might have met with a certain amount of credit among spectroscopists, had not the utterly different appearance of the magnesium fluting, as compared with the nebular line, made the matter doubtful from the outset. But this circumstance induced astronomers to inquire more closely into the question of the coincidence or non-coincidence of the nebular line with the lower edge of the magnesium fluting, and as in this respect the repeated researches of HUGGINS showed, unmistakably, that the nebular line was the more refrangible one, the question seemed decided. From a renewed discussion of previous observations on the position of the chief nebular line, up to 1870, LOCKYER nevertheless concluded that the coincidence in question was perfect, and his own observations of the *Orion* nebula, with a spectroscope of the old KIRCHHOFF form, only confirmed this conclusion. But it is obvious that a spectroscope of this description is much too crude for the unambiguous distinction between spectrum places of so great vicinity as here concerned.

At the request of HUGGINS, Professor KEELER was induced to take up the question with the great instrumental means of the LICK Observatory. The examination of the nebulæ G. C. 4234 (Σ 5) and G. C. 4373, with a diffraction grating of 14438 lines to the inch, fully confirmed the opinion of HUGGINS in regard to the non-coincidence of the nebular line with the terminal line of the magnesium fluting. But, besides this, such an appreciable difference in the positions of the chief line in the two nebulæ was observed, that a considerable motion in the line of sight of one or both objects must be assumed. This circumstance induced Professor KEELER to extend the investigation to a great many nebulæ, of which ten presented the chief line bright enough for

an accurate determination of its place. From the mean of these ten nebulæ the wave-length $\lambda = 5005.68$ in ÅNGSTRÖM'S Units (A. U.) resulted—deduced, of course, under the provisional supposition that the motions of the single nebulæ compensated each other in the mean. After a determination of the radial velocity of the *Orion* nebula, in the winter of 1890–91, by means of its hydrogen line, the normal position of the chief line was corrected to $\lambda = 5005.93$.*

After these introductory remarks, Professor KEELER, in the next two chapters (II and III) gives a detailed description of the apparatus employed and of very elaborate experiments on instrumental errors. The star spectroscope used in connection with the 36-inch refractor was made by BRASHEAR, after drawings by Professor KEELER himself. For the particulars of its construction the original memoir must be consulted, it being sufficient here to mention only the most prominent features. Thus, the objectives of both collimator and observing telescope were made of Jena glass, with clear apertures of 1½ and focal lengths of 20 inches. A second observing telescope of only 10 inches focus is also provided. The dispersive part of the instrument consists of a ROWLAND grating with a ruled surface of $2\frac{1}{16}$ x $3\frac{3}{16}$ inches and 14438 lines to the inch. This grating can, if desired, be changed for a prism of 30°, 60°, or for a compound one of about three and a half times the dispersion of the 60° prism. The whole instrument is connected with the refractor by means of two heavy brass tubes, inserted by clamps in a large collar surrounding the tailpiece of the telescope tube, and provided with position-circle and slow motion. All the appliances necessary for adjustment of the spectroscope are provided.

For the determination of spectrum places by relative measurements, a micrometer, the value of a revolution of which is 3′ 10″.8, is adapted to the observing telescope; and, besides this, a 60° reflecting prism permits the introduction of comparison spectra. But absolute determinations of wave-lengths are also possible, the grating-table being to this end connected with a graduated circle divided on the edge to 10′, and which, by two verniers can be read to 10″.

Before employing the above-described instrument in the deli-

---

* According to ÅNGSTRÖM'S scale. On account of circumstances well known to spectroscopists, Professor KEELER, in his subsequent researches, has adopted the scale of ROWLAND.

cate observations here concerned, the author made very careful researches on the errors which may possibly arise through imperfect adjustment and other causes. In this regard the arrangement of the comparison apparatus is of the first importance, it being next to certain that a great part of the discrepancies of former observations among themselves is to be attributed to imperfections in this regard. The essential condition that the same lines in the direct and reflected spectrum shall always be in exact coincidence, was insured here by causing the two pencils of rays to pursue the same path in the instrument; and different trials with the spectra of sodium, magnesium and solar light, showed that a perfect adjustment was attained. That the usual adjustments of the collimator with respect to the optical axis of the great telescope, the micrometer wires, and the slit, in relation to the focal planes of the observing telescope and the collimator, were carefully effected, scarcely needs to be pointed out. Further, the influence of flexure was tested by measuring the distance $\Delta\lambda$ between the lead line λ 5005.6 and the chief line in the *Orion* nebula, in four different positions of the spectroscope, obtained by rotating the whole about the axis of the refractor. The results were :

Position-circle at 30°	$\Delta\lambda = 2.09$ (A. U.)
120	.15
210	.03
300	.01
30	.10
	2.08 ± 0.02

It is evident from these figures that no appreciable error due to flexure exists in these visual observations. As further repeated determinations of the distance of the chief nebular line in the spectrum of G. C. 4390 from the above-named lead line, executed both with the grating and with the compound prism, were in satisfactory accordance, it is plain that systematic errors of any sensible amount could be regarded as not existing.

The author next passes to the description of his method of observation. In all measurements of the position of the spectral lines in the nebulæ the ROWLAND grating was used. The observations, which were mainly differential, the nebular lines being referred to suitably situated metallic lines introduced by the comparison prism, were taken either in the third or fourth order.

The slit was narrowed so that the bright lines of the nebula or the comparison spectrum equalled the apparent width of the micrometer wire, and the settings made by occulting the lines by the latter. Any possible personal error in setting the micrometer was eliminated by executing the observations alternately on opposite sides of the instrument. For the reduction of the measured distances to differences of wave-length, the following values of the micrometer revolution, obtained by measures in the solar spectrum, were used :

At.	III Order.	IV Order.	
D	$1^r.0 = 3.29$		
b	3.60	2.10	
Neb. 1	3.71	2.21	A. U.
Neb. 2	3.73	2.24	
H_β	3.75	2.28	

As comparison lines in the differential measures he used, for the chief nebular line, a very thin and sharp line in the lead spectrum at λ 5005.6, and the marginal line of the magnesium fluting at λ 5007.5, between which the nebular line usually lies; and for the second nebular line he used the iron line at λ 4957.6. The use of the magnesium fluting was afterwards abandoned, experience showing that the accuracy of the observations was not impaired by referring them only to the lead line. The exact positions of these lines on ROWLAND'S scale, as determined in his laboratory by Mr. JEWELL and adopted by the author, are the following :

Magnesium fluting, edge,	$\lambda = 5007.473$
Pb	$= 5005.634$
Fe	$= 4957.634$

Of these lines that of iron is double, with the components 4957.786 and 4957.482; but as they could not be separated with the slit-width used in nebular observations, the measurements refer to the center of the pair.

In order to show the accuracy of the measures, various examples of observations are given in the fourth and seventh chapters. Part of these are observations of planets and stars made during the course of the observations of nebulæ, as a check of the instrumental adjustments. Of these measures it may be convenient here to give the following as specimens of

the exceedingly high accuracy attained by the author. If we denote by λ, n, the wave-length and micrometer reading for the observed line in the spectrum of the heavenly body, and by λ_o, n_o, the corresponding quantities for the comparison line, then we have

$$\lambda = \lambda_o + r\,(n - n_o)$$

where r denotes the value of the micrometer revolution as given above.

I. 1890 JULY 17. G. C. 4390 (Σ 6).

COMPARISON OF THE CHIEF LINE WITH Pb AND Mg, IV ORDER.

Neb.	Pb.	Δ	Neb.	Mg.	Δ
$4^r.72$	$4^r.12$	+ 0.60	$4^r.76$	$4^r.98$	− 0.22
.75	.13	.62	.70	.96	.26
.74	.12	.62	.71	.95	.24
.72	.08	.64	.69	.93	.24
.70	.09	.61	.74	.92	.18
.67	.01	.66			
.78	.14	.64			
		0.627			− 0.228

0.627 r =	1.39 A. U.	− 0.228 r =	− 0.51 A. U.
Pb λ :	5005.63	Mg λ :	5007.47
Neb.	5007.02		5006.96

Mean,	5006.99
Earth's motion,	− 0.17
∴ Neb. λ =	5006.82

II. OBSERVATIONS OF *VENUS*.

	Displacement of D.	Observed Motion.	Calculated Motion.	C.-O.
1890 Aug. 16	−0.070	−7.3	−8.1	−0.8 miles
22	−0.085	−8.9	−8.2	+0.7
22	−0.072	−7.5	−8.2	−0.7
30	−0.070	−7.3	−8.3	−1.0
Sept. 3	−0.079	−8.2	−8.3	−0.1
4	−0.079	−8.2	−8.3	−0.1
1891 Mch. 21	+0.062	+6.5	+7.9	+1.4
Apr. 3	+0.061	+6.4	+7.7	+1.3

α Bootis.

			Displacement of D.	Observed Motion.	Earth's Motion.	Motion of Star referred to Sun.
1890	Apr.	10	$-0^{\mathrm{r}}.044$	− 4.6 miles	− 0.6	−4.0
	Aug.	7	+0.100	+10.4	+14.3	−3.9
		15	+0.089	+ 9.3	+13.3	−4.0
1891	Mch.	16	−0.106	−11.1	− 7.3	−3.8
		20	−0.121	−12.7	− 6.3	−6.4
	Apr.	2	−0.053	− 5.5	− 2.9	−2.6
		29	−0.003	0.0	+ 4.3	−4.3
	May	8	+0.024	+ 2.5	+ 6.6	−4.1
		14	+0.031	+ 3.2	+ 8.0	−4.8
						−4.2 ± 0.2

The above specimens are sufficient to show at the same time the great accuracy of the measures and their freedom from appreciable errors by want of adjustment of the spectroscope. Indeed, a probable error of only ±0.2 miles for the radial velocity of a star is an accuracy which hitherto has only been reached in the Potsdam photographic determinations, but which, in visual observations, could hardly have been hoped for.

The chemical origin of the chief nebular line being unknown, its normal position, *i. e.*, the position which it would have if the observer and the nebula were at rest relatively to each other, cannot be determined unless the motion can be ascertained in some nebula with help of the third line, which undoubtedly belongs to hydrogen. Hence, the determination of the radial velocities of the nebulæ depend on such a measurement.

Among the nebulæ observed by the author, only two, the *Orion* nebula and G. C. 4390, were bright enough to permit a direct comparison with the hydrogen spectrum. On this account it seems convenient to give here in full the determinations obtained for these two objects.

(*a*) The *Orion* Nebula.

The observations were always made in the same part of the nebula immediately preceding the trapezium, in order to have them all undisturbed by any possibly existing rotary motion of its different parts. The results are embodied in the following tables :

I. Position of the Chief Line.

		Order.	Distance from Pb. Line.	Observed λ	Correction for Earth's Motion.	λ
1890	Feb. 13	IV	+2.13 A.U.	5007.76	−0.39	5007.37
	13	III	1.92	07.55	−0.39	.16
	Mch. 20	IV	2.08	07.71	−0.43	.28
	Oct. 10	IV	1.32	06.95	+0.39	.34
	16	IV	1.51	07.14	+0.36	.50
	17	IV	1.34	06.97	+0.36	.33
	17	III	1.39	07.02	+0.36	.38
	23	IV	1.49	07.12	+0.33	.45
	23	III	1.48	07.11	+0.33	.44
	30	IV	1.38	07.01	+0.30	.31
	30	III	1.34	06.97	+0.30	.27
1891	Jan. 23	III	2.04	07.67	−0.30	.37
	23	IV	1.97	07.60	−0.30	.30
	26	IV	2.02	07.65	−0.31	.34
	28	IV	2.09	07.72	−0.32	.40
	Feb. 12	IV	2.08	07.71	−0.39	.32
	Apr. 3	IV	+2.04	07.67	−0.40	.27
						5007.34 ± 0.013

II. Motion of the Nebula from Comparison of the Third Line with H_β.

		Order.	Displacement of Nebular Line.	Observed Motion. Miles.	Earth's Motion. Miles.	Motion of Nebula referred to Sun. Miles.
1890	Oct. 16	III	−0ʳ.019	− 2.7	−13.6	+10.9
	23	III	− .003	− 0.4	−12.4	12.0
	23	III	− .019	− 2.7	−12.4	9.7
	30	III	− .050	− 7.2	−11.2	4.0
1891	Jan. 23	IV	+ .241	+19.4	+11.0	8.4
	23	III	+ .191	+25.8	+11.0	14.8
	26	III	+ .125	+16.9	+11.6	5.3
	28	III	+ .233	+33.5	+12.0	21.5
	Feb. 12	IV	+ .307	+26.9	+14.5	12.4
	12	III	+ .183	+26.3	+14.5	11.8
	Mch. 6	IV	+ .284	+24.9	+16.2	8.7
	18	IV	+ .338	+29.6	+16.1	13.5
	20	IV	+0.300	+26.3	+16.1	10.2
					Mean,	11.0±0.8

The nebula thus receding from the solar system at a rate of 11 miles, the third line is displaced toward the red by nearly 0.29 A. U., and also the chief line by nearly the same amount. Thus, its normal position would be

$$5007.34 - 0.29 = 5007.05.$$

(*b*) G. C. 4390.

On account of the great brightness of this nebula, the position of the chief line could be determined very accurately, as will be seen from the following table, in which the observed values have been reduced by referring the line both to the lead line and to the magnesium fluting.

I. Position of the Chief Line.

	Observed λ.	Red. to Sun.	λ
1890 July 10	5007.06	— 0.12	5006.94
17	06.99	— .17	.82
24	07.18	— .22	.96
25	07.14	— .22	.92
25	07.18	— .21	.97
31	07.16	— .26	.90
Aug. 1	07.14	— .27	.87
7	07.18	— .29	.89
8	07.25	— .30	.95
1891 Apr. 29	06.53	+ .34	.89
May 8	06.59	+ .30	.89
14	06.56	+ .26	.82
22	06.58	+ .22	.80
			5006.89

II. Comparison of the Third Line with H_β, IV Spectrum. Nebular Line Displaced Toward Red.

1891 May 21. Neb. Line — H_β.	May 22. Neb. Line — H_β.
— 0^r.157	— 0^r.183
.176	.155
.141	.188
.201	.231
.201	.154

1891 May 21. Neb. Line — $H\beta$.	May 22. Neb. Line — $H\beta$.
.163	.160
.146	.173
.144	.120
.196	.176
.167	.091
0.169	— 0.163

Observed motion,	— 14.8 miles.	— 14.3
Earth's "	— 8.0	— 8.0
Nebula to Sun,	— 6.8	— 6.3

Mean, — 6.55 miles.

From this velocity towards the solar system it follows that the chief line is displaced towards the violet by

0.18 A. U.,

and that the normal position is

$$5006.89 + 0.18 = 5007.07.$$

The close agreement between this value and that derived from the *Orion* nebula is indeed highly satisfying, and the best proof of the truly surprising accuracy attained by the author in his observations.

It would be superfluous, in the present abstract, to transcribe more specimens of the rich material of observations accumulated by the author in his memoir. But, on comparing the resulting wave-lengths for the chief line in the different nebulæ as referred to the Sun, differences are found which many times exceed the small probable errors. These differences can only depend upon radial motions of the nebulæ relatively to the solar system. By comparison with the normal position of the chief line as deduced above, it is therefore possible to calculate the velocities of these motions. The results of such a determination for the nebulæ of sufficient brightness to permit a satisfactory measurement of the chief line are given in the following table :

Nebula.	λ	Displacement.	Motion, miles.
Orion.	5007.34 ± .013	+ 0.29 ± .02	+ 11.0 ± 0.8
G. C. 826	06.88	— 0.17	— 6.3
G. C. 2102	07.15 ± .04	+ 0.10 ± .05	+ 3.7 ± 1.8
G. C. 4234 (Σ 5)	06.48 ± .02	— 0.57 ± .03	— 21.3 ± 1.3
G. C. 5851	06.19	— 0.86	— 32.0
G. C. 4373	05.97 ± .04	— 1.08 ± .05	— 40.2 ± 1.8
G. C. 4390 (Σ 6)	06.89 ± .01	— 0.16 ± .03	— 6.0 ± 1.2
N. G. C. 6790	07.86	+ 0.81	+ 30.1
G. C. 4510	06.77	— 0.28	— 10.4 ± 2.8
G. C. 4514	06.96 ± .02	— 0.09 ± .03	— 3.3 ± 1.5
N. G. C. 6891	07.73	+ 0.68	+ 25.3 ± 4.0
G. C. 4628	06.22 ± .04	— 0.83 ± .05	— 30 9 ± 1.8
N. G. C. 7027	07.22 ± .01	+ 0.17 ± .03	+ 6.3 ± 1.2
G. C. 4964	06.86	— 0.19	— 7.1 ± 3.0

The positive sign signifies recession, the negative approach. The probable errors are combinations of the corresponding quantities for the measurements and for the normal position of the chief line. The author divides the nebulæ in two groups: very bright (I), and bright (II), and finds

	Probable Error of Displacement.		No. of Observations.
I	$\epsilon = \pm$ 0.058 A. U.	= ± 2.2 miles	1
	= .046	1.7	2
	= .039	1.5	4
II	$\epsilon = \pm$ 0.104	± = 3.9	1
	.077	2.9	2
	.058	2.2	4

From the above table it is seen that motions of approach preponderate. This is only a consequence of the fact that the greater part of the examined nebulæ are situated in the same region of the sky as the apex of the solar motion.

It cannot be but regretted that determinations of the places of nebulæ, with any exactitude approaching that obtained for the stars, are hitherto almost absolutely wanting. Thus every idea, not only of their parallaxes, but also of their proper motion, is, with exception of perhaps the sole instance of the *Trifid* nebula, for a long time to come, out of question. And yet the knowledge of these quantities is the *conditio sine qua non*, in combination with the spectroscopically determined radial velocities, to get any

notion of their real movements. On reflecting upon these matters, one is almost inclined to consider the employment of the great refractors of to-day in prolonged observations of the old members of the planetary system of asteroids, comets, and such, as abuse of means; because in most cases, for researches of this class, instruments of medium size would suffice; whereas, for a systematic scrutiny of the nebular world, only from the greatest optical powers can be expected any progress worthy of consideration.

Besides the position of the chief line, that of the second line, in a number of nebulæ, has been determined by comparison with the iron spectrum, or by measuring its distance from the chief line by means of the graduated circle of the spectroscope. In the former case the apparent position was first corrected for the orbital motion of the Earth, and then, by means of the known radial motion of the nebula, reduced to its normal value. In the second case the final result is deduced by subtracting the measured interval from the normal place of the chief line. Thus the following results were obtained :

(*a*) NORMAL POSITION OF THE SECOND NEBULAR LINE FROM COMPARISON WITH THE IRON LINE 4957.63.

Nebula.	λ	Motion of Nebula.	Correction for Motion.	Normal λ
Orion	4959.33	+ 11.0 miles	− 0.29	4959.04
G. C. 2102	59.06	+ 3.7	− 0.10	58.96
G. C. 4373	57.98	− 40.2	+ 1.07	59.05
G. C. 4390	58.90	− 6.0	+ 0.16	59.06
N. G. C. 7027	59.15	+ 6.3	− 0.17	58.98
				4959.02 ± 0.04

(*b*) NORMAL POSITION OF THE SECOND NEBULAR LINE DEDUCED FROM THE POSITION OF THE FIRST LINE.

Nebular.	λ
Orion	4958.92
G. C. 4373	59.14
G. C. 4373	59.01
G. C. 4390	59.16
N. G. C. 7027	58.98
N. G. C. 7027	59.23
	4959.07 ± 0.03

The agreement is, as seen, in every way excellent.

In virtue of the above-exposed results, the validity of LOCKYER'S opinion regarding the relation of the chief nebular line to the green fluting of the magnesium flame spectrum is easily tested. The normal position of the nebular line is, as we have seen,

From observations of the *Orion* nebula	$\lambda = 5007.05$
From observations of G. C. 4390	.07
	5007.06

Whereas the position of the edge of the magnesium fluting, according to Mr. JEWELL, is

$$\lambda = 5007.47.$$

The difference, 0.41 A. U., is about fourteen times greater than the probable error of observation, and must therefore, on account of the absence of sensible systematic errors in the observations, be considered as real. This fact is alone sufficient to make any connection between the two impossible. It is much more the case since, even on the supposition of exact coincidence between two single lines in a celestial and metallic spectrum, the reality of a connection between them is therefore by no means proved. To make such a connection, on the whole, probable, not only the position, but also the external features of the compared lines must, of course, be identical. In the present instance, however, the numerous observations and experiments, which the author has instituted with the view to test this question, show a decidedly negative result; and hence the observations of the hazy character of one side of the chief nebular line formerly recorded must have resulted from instrumental imperfections.

After an exposition of some views regarding the origin of the nebular lines and the constitution of the nebulæ in general, founded upon the observations detailed in the preceding chapters, the author finally sums up the results to which his researches have led him. The essential part of these results has, it is hoped, been sufficiently pointed out in the preceding pages of this brief extract. For the great many spectroscopic and other details contained in Professor KEELER'S memoir, the original must be consulted. The reader will then find a rich reward and assuredly agree with the present writer in congratulating Professor KEELER on having made, in this work, the first really important progress in a domain of the spectroscopy of precision in which the most eminent spectroscopists have hitherto in vain exerted themselves.

STOCKHOLM ACADEMY OF SCIENCES. December, 1894.